

# Holographic QCD predictions for production and decay of pseudoscalar glueballs

Frederic Br  nner and Anton Rebhan

*Institut f  r Theoretische Physik, Technische Universit  t Wien,  
Wiedner Hauptstrasse 8-10, A-1040 Vienna, Austria*

(Dated: November 1, 2016)

The top-down holographic Witten-Sakai-Sugimoto model for low-energy QCD, augmented by finite quark masses, has recently been found to be able to reproduce the decay pattern of the scalar glueball candidate  $f_0(1710)$  on a quantitative level. In this Letter we show that this model predicts a narrow pseudoscalar glueball heavier than the scalar glueball and with a very restricted decay pattern involving  $\eta$  or  $\eta'$  mesons. Production should be either in pairs or in association with  $\eta^{(\prime)}$  mesons. We discuss the prospect of discovery in high-energy hadron collider experiments through central exclusive production by comparing with  $\eta'$  pair production.

PACS numbers: 11.25.Tq, 13.25.Jx, 14.40.Be, 14.40.Rt

## INTRODUCTION

Quantum chromodynamics, the established theory of the strong interactions, predicts [1] the existence of flavor singlet mesons beyond those required by the quark model, because in the absence of quarks gluons by themselves can form bound states. However, the status of such “gluonium” or “glueball” states in the observed meson spectrum is still unclear and controversial [2–5].

In 1980, an isoscalar pseudoscalar with mass around 1.44 GeV which is copiously produced in the gluon-rich radiative decays of  $J/\psi$  was proposed as the first glueball candidate [6]. Originally named  $\iota(1440)$  [7], this is now listed by the Particle Data Group [8] as the two states  $\eta(1405)$  and  $\eta(1475)$ . Together with  $\eta(1295)$ , this indeed would give rise to a supernumerary state beyond the first radial excitations of the  $\eta$  and  $\eta'$  mesons, with  $\eta(1405)$  singled out as glueball candidate [9].

The situation thus appears to be analogous to the case of the scalar glueball, which is generally considered to give rise to a supernumerary state in the set of isoscalar scalar resonances  $f_0(1370)$ ,  $f_0(1500)$ , and  $f_0(1710)$ , where only two are expected from the quark model (namely linear combinations of  $\bar{u}u + \bar{d}d$  and  $\bar{s}s$ ). Here the discussion is divided on the question which of the two heavier resonances has the larger glueball contribution [10–14].

However, only the case of the scalar glueball candidates is supported by existing lattice QCD calculations [15, 16] which consistently find that the lowest-lying glueball state has mass around 1.7 GeV and quantum numbers  $J^{PC} = 0^{++}$ . The lowest-lying pseudoscalar glueball state is instead found to have a mass around 2.6 GeV, somewhat higher than the  $2^{++}$  tensor glueball with mass around 2.4 GeV. Most lattice results have been obtained in the quenched approximation [17], i.e. without dynamical quarks, but recent unquenched lattice calculations [18, 19] have found no evidence for significant unquenching effects, which however should be expected if the pseudoscalar glueball were to mix strongly with radi-

ally excited  $\eta^{(\prime)}$  mesons. Moreover, it is still a controversial issue whether all three states  $\eta(1295)$ ,  $\eta(1405)$ , and  $\eta(1475)$  really exist [20].

We thus assume that the pseudoscalar glueball still has to be discovered and that it should be searched for in the mass range 2–3 GeV. Unfortunately, lattice QCD does not (yet) give information on the production and decay patterns of a pseudoscalar glueball, whereas phenomenological models are weakly constrained with regard to the particular form of pseudoscalar glueball interactions. [21]

In this work we show that rather specific predictions can be obtained from the Witten-Sakai-Sugimoto (WSS) model for low-energy QCD, which is a top-down string-theoretic construction in the large color number ( $N_c$ ) limit with only one free dimensionless parameter. Extrapolated to  $N_c = 3$ , it reproduces several experimental results in hadron physics to within 10–30% [22, 23]. In Ref. [23] we have applied this model to calculate decay rates of scalar and tensor glueballs in the chiral limit, and in [24, 25] with quark masses included. In the latter case we found a strong “nonchiral enhancement” of the decay of a predominantly dilatonic glueball into kaons and  $\eta$  mesons which quantitatively agrees remarkably well with the data for the glueball candidate  $f_0(1710)$  as far as presently known (provided the not-yet-measured decay rate into  $\eta$ - $\eta'$  pairs is sufficiently small [25]). This suggests that  $f_0(1710)$  could be a nearly pure glueball, in agreement with recent phenomenological models that favor  $f_0(1710)$  as the scalar glueball [11, 12] with comparatively small admixture of light quarkonia.

In this Letter we explore the implications of the WSS model for production and decay of the long-sought-after pseudoscalar glueball under the assumption that this very predictive approach based on the large- $N_c$  limit with largely unmixed glueballs can indeed give the right hints for real QCD.

While in Ref. [23] our WSS model prediction for the width of the tensor glueball of mass  $\gtrsim 2$  GeV was very large, perhaps too large to be clearly observable, here we arrive at the prediction of a narrow pseudoscalar glue-

ball state with a very restricted decay pattern which will be a conspicuous feature as long as mixing with quarkonia is small. The specific interactions also suggest that the pseudoscalar glueball may be difficult to produce in radiative charmonium decay, but could be a very interesting object for glueball searches in central exclusive production (CEP) experiments at sufficiently high energies.

### EFFECTIVE LAGRANGIAN FOR PSEUDOSCALAR GLUEBALL INTERACTIONS

The WSS model is an extension of the Witten model [26] for nonsupersymmetric and nonconformal low-energy QCD based on D4 branes in type-IIA supergravity compactified on a circle and subjected to a consistent truncation of Kaluza-Klein states. It possesses an interesting spectrum of glueball states with  $J^{PC} = 0^{++}, 2^{++}, 0^{-+}, 1^{+-}, 1^{--}$  [27] whose mass scale is set by the Kaluza-Klein mass  $M_{\text{KK}}$ . Sakai and Sugimoto [28, 29] showed that  $N_f \ll N_c$  chiral quarks can be added through probe D8 and anti-D8 branes separated on the compactification circle, which introduces a purely geometric realization of nonabelian chiral symmetry breaking  $U(N_f)_L \times U(N_f)_R \rightarrow U(N_f)_V$ . The resulting effective chiral theory involves Goldstone pseudoscalars and a tower of vector and axial vector mesons.

Fixing  $M_{\text{KK}}$  through the experimental value of the  $\rho$  meson mass and varying the 't Hooft coupling  $\lambda = 16.63 \dots 12.55$  such that either the pion decay constant (as originally done in [28, 29]) or the string tension in large- $N_c$  lattice simulations [30] is matched leads to quantitative predictions which are in the right ballpark when extrapolated to  $N_c = 3$  QCD [22]. In particular, it reproduces remarkably well the observed hadronic decay rates of the  $\rho$  and the  $\omega$  mesons, which motivates the use of the WSS model also as a model for glueball decay [23, 31]. In Ref. [23] we argued, however, that the lightest scalar glueball mode considered in Ref. [31] which comes from an “exotic polarization” of the dual graviton along the compactified direction (denoted by  $G_E$  in the following) should be discarded and that instead the predominantly dilatonic mode ( $G_D$ ) be identified with the glueball ground state.

The chiral WSS model correctly incorporates the chiral anomaly and the Witten-Veneziano mechanism for giving mass to the flavor singlet pseudoscalar  $\eta_0$  with [28, 32, 33]  $m_0^2 = N_f \lambda^2 M_{\text{KK}}^2 / 27\pi^2 N_c$ . Introducing explicit quark mass terms in the effective Lagrangian such that physical pion and kaon masses are matched leads to  $\eta$  and  $\eta'$  masses that agree with real QCD to within  $\lesssim 10\%$  [24, 25]. As mentioned above, the flavor-asymmetric decay pattern observed for the scalar glueball candidate  $f_0(1710)$  can be reproduced quantitatively with  $G_D$ , if the (as yet undetermined) parameter for scalar glueball couplings to explicit quark mass terms is chosen such that

the rate of decay into mixed  $\eta\eta'$  pairs remains small.

The interaction Lagrangian of the pseudoscalar glueballs is the same for both, the chiral and the massive version of the WSS model. The pseudoscalar glueball modes are provided by a Ramond 1-form field  $C_1$  which plays the central role in producing the Witten-Veneziano mass  $m_0$ . Following the notation of Ref. [28], the action for  $C_1$  is given by  $S_{C_1} \propto \sqrt{-g} |\tilde{F}_2|^2$ . Cancellation of the  $U(1)_A$  anomaly requires that  $\tilde{F}_2$  is a gauge invariant combination of  $F_2 = dC_1$  and the field  $\eta_0 = (f_\pi / \sqrt{2N_f}) \int dz \text{Tr} A_z(z, x)$  with  $z$  parametrizing the radial extent of the joined D8 and anti-D8 branes on which the flavor gauge field  $A$  lives.

Inserting a mode expansion of the Ramond 1-form field  $C_1$  with 4-dimensional pseudoscalar glueball fields  $\tilde{G}^{(n)}(x)$ ,  $n = 1, \dots$ , together with scalar and tensor glueball fields entering through the metric in  $S_{C_1}$  leads to the effective 4-dimensional Lagrangian

$$\mathcal{L}_{C_1}^{\text{eff}} = -\frac{1}{2} \partial_\mu \tilde{G} \partial^\mu \tilde{G} - \frac{1}{2} m_P^2 \tilde{G}^2 - \frac{1}{2} m_0^2 \eta_0^2 + \mathcal{L}_{\eta_0^2 G} + \mathcal{L}_{\tilde{G} \eta_0 G} + \mathcal{L}_{\tilde{G}^2 G} + O(G_{D,E,T}^2) \quad (1)$$

(suppressing the summation over the mode number index ( $n$ )). Here  $O(G_{D,E,T}^2)$  denotes higher-order interactions involving terms quadratic in  $\tilde{G}$ ,  $\eta_0$  and quadratic or higher in the glueball fields arising from metric fluctuations (the tensor glueball field  $T^{\mu\nu}$  appears at most linearly, but also has interactions involving arbitrarily high powers of the scalar glueball field).

The mass of the lowest pseudoscalar glueball mode ( $n = 1$ ) is [27]  $M_P \approx 1.885 M_{\text{KK}}$ , which like in lattice QCD results is above the mass of the scalar and tensor glueballs with  $M_D = M_T \approx 1.567 M_{\text{KK}}$ . With  $M_{\text{KK}} = 949$  MeV from having matched the mass of the  $\rho$  meson,  $M_D \approx 1487$  MeV and  $M_P \approx 1789$  MeV, but in the eventual applications we shall leave  $M_P$  a free parameter and either keep  $M_D$  at 1.5 GeV which approximately matches the mass of  $f_0(1500)$  or artificially raise its mass to the mass of  $f_0(1710)$ .

Note that Eq. (1) contains a mass term for the flavor singlet  $\eta_0$  [28], but no mixing of the pseudoscalar glueball modes  $\tilde{G}^{(n)}$  with  $\eta_0$ . Terms proportional to  $\eta_0 \tilde{G}^{(n)}$  vanish in the unperturbed background geometry, but appear in the presence of metric fluctuations dual to scalar glueballs. In the WSS model, such terms are the only ones which can mediate a decay of pseudoscalar glueballs. Explicitly they read (keeping the exotic glueball mode  $G_E$  for completeness)

$$\mathcal{L}_{\tilde{G} \eta_0 G} = \tilde{d}_0 \tilde{G} \eta_0 G_D + \tilde{c}_0 \tilde{G} \eta_0 G_E + \frac{\tilde{c}_0'}{M_E^2} \partial_\mu \tilde{G} \eta_0 \partial^\mu G_E + \tilde{c}_0'' \tilde{G} \eta_0 \frac{\square - M_E^2}{M_E^2} G_E \quad (2)$$

with the numerical results for the coupling constants for the lowest pseudoscalar glueball mode listed in Table I (their integral representations will be given elsewhere).

coeff.	value
$\bar{d}_0$	$17.915 \lambda^{-1/2} N_c^{-1} M_{\text{KK}}^{-1}$
$\tilde{d}_0$	$2.5833 \lambda^{1/2} N_f^{1/2} N_c^{-3/2} M_{\text{KK}}$
$\tilde{d}_1$	$42.484 \lambda^{-1/2} N_c^{-1} M_{\text{KK}}^{-1}$
$\tilde{d}_2$	$27.106 \lambda^{-1/2} N_c^{-1} M_{\text{KK}}^{-1}$
$\check{c}_0$	$15.829 \lambda^{-1/2} N_c^{-1} M_{\text{KK}}^{-1}$
$\bar{c}_0$	$26.837 \lambda^{-1/2} N_c^{-1} M_{\text{KK}}^{-1}$
$\tilde{c}_0$	$-4.8795 \lambda^{1/2} N_f^{1/2} N_c^{-3/2} M_{\text{KK}}$
$\check{c}'_0$	$1.6306 \lambda^{1/2} N_f^{1/2} N_c^{-3/2} M_{\text{KK}}$
$\tilde{c}''_0$	$2.0502 \lambda^{1/2} N_f^{1/2} N_c^{-3/2} M_{\text{KK}}$

TABLE I. Coupling constants in the glueball interaction Lagrangians (2), (3), and (4).

The part of the action which leads to the Witten-Veneziano mass term also gives rise to interactions with scalar glueballs which were obtained (on-shell) in [24]. To linear order in glueball fields the corresponding interaction Lagrangian reads (also including an extra off-shell contribution for the exotic mode  $G_E$ )

$$\mathcal{L}_{\eta_0^2 G} = \frac{1}{2} m_0^2 \eta_0^2 (3d_0 G_D - 5\check{c}_0 G_E) + \frac{1}{2} \bar{c}_0 m_0^2 \eta_0^2 \frac{\square - M_E^2}{M_E^2} G_E. \quad (3)$$

There are also interaction terms of the form  $(\partial\eta_0)^2 G_{D,E,T}$  coming from the DBI action of the D8 branes, which can be found in Ref. [23], as well as natural-parity violating terms  $\eta_0 G_T^2$  from Chern-Simons action of the D8 branes, which have been obtained in Ref. [34].

Interaction terms involving pairs of pseudoscalar glueballs and a scalar or tensor glueball are given by

$$\mathcal{L}_{\tilde{G}^2 G} = \tilde{d}_1 \left[ \frac{1}{2} \partial_\mu \tilde{G} \partial^\mu \tilde{G} - \frac{1}{8} \partial_\mu \tilde{G} \partial_\nu \tilde{G} \frac{\partial^\mu \partial^\nu}{\square} \right] G_D + \frac{1}{2} \tilde{d}_2 m_P^2 \tilde{G}^2 G_D + \frac{\sqrt{6}}{8} \tilde{d}_1 \partial_\mu \tilde{G} \partial_\nu \tilde{G} T^{\mu\nu} + \mathcal{L}_{\tilde{G}^2 G_E}. \quad (4)$$

(The more unwieldy expression  $\mathcal{L}_{\tilde{G}^2 G_E}$  will be given elsewhere.)

### DECAY PATTERN OF THE PSEUDOSCALAR GLUEBALL

The only interaction terms arising within the WSS model that are relevant for the decay of pseudoscalar glueballs are contained in (2). They differ strongly from the leading interaction terms that have been assumed previously in phenomenological models.

Rosenzweig et al. [35, 36] have assumed that the chiral anomaly is not saturated by  $\eta_0$  alone, but involves a further physical pseudoscalar field ( $\tilde{G}_2$ ) [37], which couples

to the imaginary part of  $\log \det \Sigma$ , where  $\Sigma$  is the matrix of  $q\bar{q}$  states (which is unitary in the nonlinear sigma model, involving only the pseudoscalars, but unrestricted in linear sigma models [38] so that it also accommodates scalar mesons). While a natural possibility [35] would be to identify  $\tilde{G}_2$  with the radial excitation of  $\eta_0$ , it was proposed to identify  $\tilde{G}_2$  with the pseudoscalar glueball instead. Originally used in the context of the glueball candidate  $\iota(1440)$ , this approach was also adopted in the extended linear sigma model of Ref. [39] for pseudoscalar glueballs with a mass suggested by lattice QCD. The dominant decay mode of a pseudoscalar glueball in this approach turns out to be  $K\bar{K}\pi$  (branching ratio  $\mathcal{B} \approx 1/2$ ) followed by  $\eta\pi\pi$  ( $\mathcal{B} \approx 1/6$ ) and  $\eta'\pi\pi$  ( $\mathcal{B} \approx 1/10$ ).

Using large- $N_c$  chiral Lagrangians, Gounaris et al. [40] argued that there should be no coupling of the pseudoscalar glueball to  $\text{Im} \log \det \Sigma$ . Instead, a coupling to  $\text{Im} \text{tr} \mathcal{M}_q \Sigma$  was considered so that the pseudoscalar glueball is stable in the limit of massless quarks ( $\mathcal{M}_q$  being the quark mass matrix). This again gives a dominant decay mode  $K\bar{K}\pi$ , but with  $\eta\pi\pi$  being more strongly suppressed (parametrically by a factor  $m_\pi^2/m_K^2$ ).

In agreement with the considerations of Ref. [40], the WSS model, which also corresponds to a large- $N_c$  chiral Lagrangian, does not lead to a coupling of the pseudoscalar glueball to  $\text{Im} \log \det \Sigma$ . However, its extension to finite quark masses (either through world-sheet instantons [41] or open-string tachyon condensation [42]) does not naturally lead to a coupling to  $\text{Im} \text{tr} \mathcal{M}_q \Sigma$ , because Ramond fields do not couple directly to fundamental strings. In the WSS model, the only coupling linear in  $\tilde{G}$  is to  $\eta_0 G$ . This suggests that the pseudoscalar glueball should decay dominantly in  $\eta(')$  and the  $f_0$  meson which corresponds to the scalar glueball, or  $\eta(')$  and decay products of the latter. According to the WSS model, the decay mode  $K\bar{K}\pi$  that is obtained as the dominant one in the approaches mentioned above should instead be strongly suppressed.

When the mass of the pseudoscalar glueball is larger than the mass of the scalar glueball plus the  $\eta(')$  mass, the scalar glueball can be produced on-shell. The resulting decay width is displayed in Fig. 1 as a function of the pseudoscalar glueball mass for the glueball mode  $G_D$  with mass 1.5 GeV and also when raised in mass to match  $f_0(1710)$ , which in Ref. [24] we found to be favored by the WSS model [43]. For the latter case, Fig. 2 shows the (not necessarily resonant) dimensionless partial decay widths  $\Gamma_i/M_P$  for  $\tilde{G} \rightarrow G\eta(') \rightarrow PP\eta(')$  where  $P = K, \pi, \eta, \eta'$  with the decay pattern for the scalar glueball  $G = f_0(1710)$  obtained in Ref. [24]. With  $m_P \sim 2.6$  GeV as predicted by lattice QCD, the pseudoscalar glueball is predicted to be a rather narrow state; for  $m_P \lesssim 2.3$  GeV it would be extremely narrow.

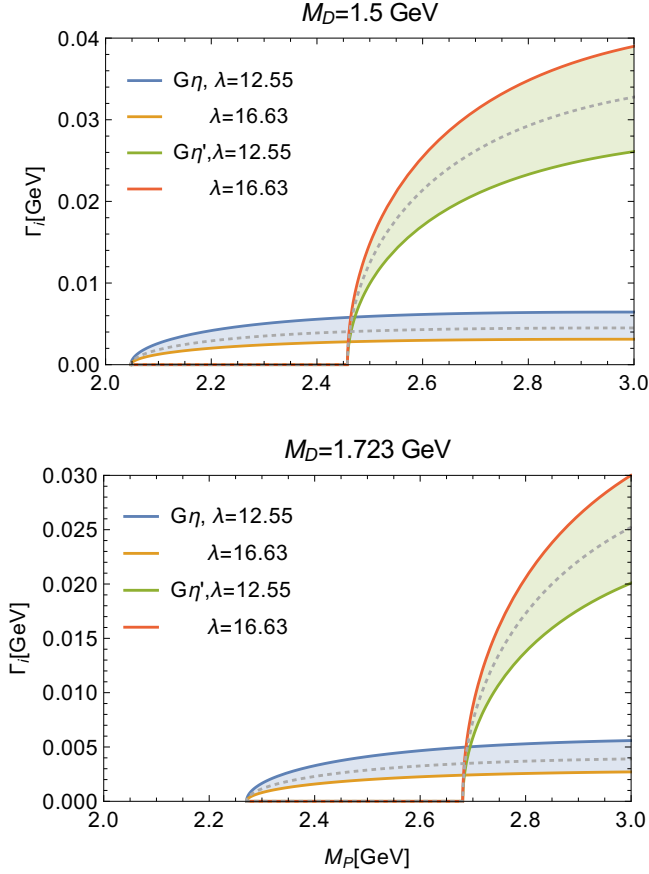


FIG. 1. Partial width of resonant decay  $\tilde{G} \rightarrow G\eta(\prime)$  (neglecting finite width of scalar glueball) for a predominantly dilatonic scalar glueball  $G_D$  with mass  $m_D = 1.5$  GeV (upper panel) and 1.723 GeV (lower panel), the latter corresponding to  $f_0(1710)$ .

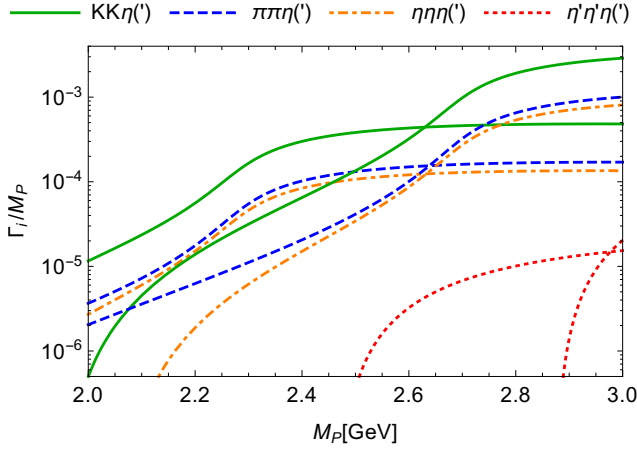


FIG. 2. Partial widths of resonant and non-resonant decays  $\tilde{G} \rightarrow G\eta(\prime) \rightarrow PP\eta(\prime)$  where  $P = K, \pi, \eta, \eta'$  assuming the decay pattern for the scalar glueball  $G = f_0(1710)$  obtained in Ref. [24]. (The two cases  $PP\eta$  and  $PP\eta'$  are plotted in the same color but can be distinguished easily by the later onset of  $PP\eta'$  which dominates at sufficiently high values of  $M_P$ .)

## PRODUCTION OF PSEUDOSCALAR GLUEBALLS

While scalar and tensor glueballs couple directly to  $q\bar{q}$  mesons, pseudoscalar glueballs do so only through the former in the WSS model. This suggests that pseudoscalar glueballs are not as easily formed in radiative decays of  $J/\psi$  as the other glueballs, but they would have to arise from excited scalar or tensor glueballs decaying into  $\eta(\prime)\tilde{G}$  or  $\tilde{G}\tilde{G}$  pairs. The thresholds for these processes are thus above the mass of the  $J/\psi$  so that excited  $\psi$  mesons or  $\Upsilon$  would be required.

Another possibility is central exclusive production (CEP) in high-energy hadron collisions through double Pomeron or Reggeon exchange (corresponding to  $G_T$  and  $(\rho, \omega)$  trajectories; pion and scalar glueball exchanges are subdominant at high energies). The parametric orders of the corresponding amplitudes are shown in Fig. 3. Here production of  $\tilde{G}\eta_0$  occurs only via virtual scalar glueballs, whereas production of  $\tilde{G}\tilde{G}$  can additionally proceed through virtual tensor glueballs. Also shown is the possibility of  $\tilde{G}\tilde{G}$  production through the natural-parity violating coupling of  $\eta_0$  to two tensor glueballs (Pomerons), which is provided by the Chern-Simons part of the action of the D8 branes and which was recently studied within the WSS model in Ref. [34].[44]

Associated production of pseudoscalar glueballs with either  $\eta(\prime)$  or other glueballs is presumably beyond the reach of the older fixed-target experiments searching for glueballs, but seem to be an exciting possibility for the new generation of CEP experiments at the LHC.

Calculation of the corresponding production cross sections within the WSS model could be attempted by employing the techniques used in Ref. [34] for  $\eta$  and  $\eta'$  production, but will be left for future work. In this Letter we only present results for the ratio of production rates of  $\tilde{G}\eta'$  and  $\tilde{G}\tilde{G}$  pairs over  $\eta'\eta'$  pairs [45], when both are produced through a virtual  $G_D$  glueball. This ratio is fixed by the vertices obtained above together with the results obtained in Ref. [24], and the result is shown in Fig. 4 for the range of 't Hooft coupling discussed above. The amplitude  $\mathcal{M}(G^* \rightarrow \tilde{G}^2) \sim \lambda^{-1/2} N_c^{-1}$  is parametrically of the same order as  $\mathcal{M}(G^* \rightarrow \eta'^2)$  so that the ratio  $N(\tilde{G}\tilde{G})/N(\eta'\eta')$  is particularly well determined (at least for fixed meson masses in the scenario of Ref. [24]) [46]. The results in Fig. 4 indicate that CEP of  $\eta'\tilde{G}$  is only one order of magnitude below CEP of  $\eta'\eta'$ , while above the threshold for  $\tilde{G}\tilde{G}$  pairs, production of the latter is even up to one order of magnitude larger than CEP of  $\eta'\eta'$ .

Central exclusive production of  $\eta'$  pairs has been studied in the Durham model in Ref. [47], where its production cross section was estimated. For example, at  $\sqrt{s} = 1.96$  TeV this work obtained  $\sigma(\eta'\eta')/\sigma(\pi^0\pi^0) \sim 10^3 \dots 10^5$  assuming sufficiently high transverse momentum such that a perturbative approach becomes justified.

Since small transverse momentum is expected to pro-

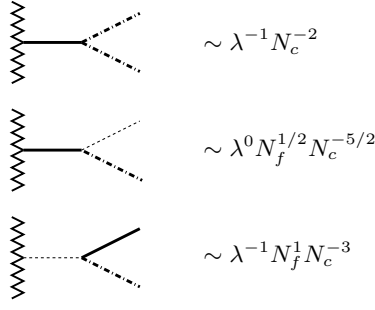


FIG. 3. Parametric orders of the production amplitudes of pseudoscalar glueballs ( $\tilde{G}\tilde{G}$ ,  $\eta(\prime)\tilde{G}$ , and  $G\tilde{G}$ , respectively) in double Pomeron or double Reggeon exchange. (Dotted, full, and dash-dotted lines represent  $\eta(\prime)$ ,  $G$ , and  $\tilde{G}$ , respectively. In the uppermost diagram the full line stands for  $G$  or  $G_T$ .)

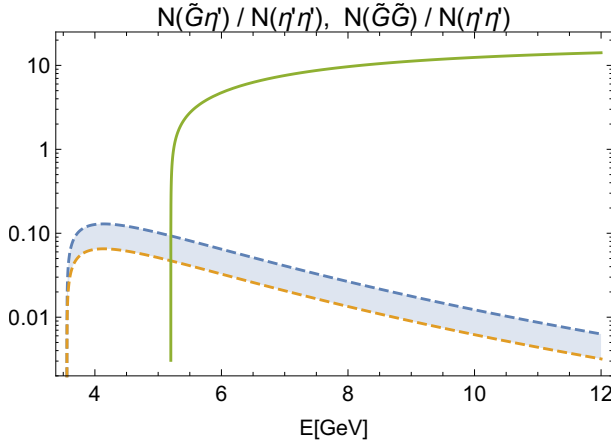


FIG. 4. Production of  $\tilde{G}\tilde{G}$  and  $\tilde{G}\eta'$  pairs versus  $\eta'\eta'$  from a virtual scalar glueball  $G_D$  for a pseudoscalar glueball mass of 2.6 GeV as functions of the center of mass energy of the produced pair. The full line gives  $N(\tilde{G}\tilde{G})/N(\eta'\eta')$ , which is independent of the 't Hooft coupling; upper and lower dashed lines correspond to  $N(\tilde{G}\eta')/N(\eta'\eta')$  with 't Hooft coupling 12.55 and 16.63, respectively.

vide a glueball filter [48, 49] and the production of  $\tilde{G}$  together with another  $\tilde{G}$  or  $\eta(\prime)$  according to the present model proceeds through virtual scalar glueballs, the kinematical regime of small transverse momentum (small azimuthal angle  $\phi_{pp}$ ) would be particularly interesting for the search of pseudoscalar glueballs.[50]

To summarize, the WSS model suggests very specific production and decay mechanisms of pseudoscalar glueballs that make them very interesting for CEP experiments at high-energy hadron colliders. All this of course assumes that pseudoscalar glueballs do not mix strongly with  $q\bar{q}$  states. At large  $N_c$  this mixing is suppressed, but it is uncertain whether this feature extends to real QCD. However the smallness of unquenching effects in glueball studies in lattice QCD found in Ref. [18, 19] could indicate that nearly pure glueballs are possible after all.

We thank Paolo Gandini, Nelia Mann, Denis Parganlija, and Ulrich Wiedner for discussions and correspondence. This work was supported by the Austrian Science Fund FWF, project no. P26366, and the FWF doctoral program Particles & Interactions, project no. W1252.

- 
- [1] H. Fritzsch and M. Gell-Mann, *Current algebra: Quarks and what else?*, *eConf* **C720906V2** (1972) 135–165, [[hep-ph/0208010](#)].  
H. Fritzsch and P. Minkowski,  $\Psi$  Resonances, Gluons and the Zweig Rule, *Nuovo Cim.* **A30** (1975) 393.  
R. Jaffe and K. Johnson, *Unconventional States of Confined Quarks and Gluons*, *Phys.Lett.* **B60** (1976) 201.
  - [2] D. Bugg, *Four sorts of meson*, *Phys.Rept.* **397** (2004) 257–358, [[hep-ex/0412045](#)].
  - [3] E. Klempt and A. Zaitsev, *Glueballs, Hybrids, Multiquarks. Experimental facts versus QCD inspired concepts*, *Phys.Rept.* **454** (2007) 1–202, [[arXiv:0708.4016](#)].
  - [4] V. Crede and C. Meyer, *The Experimental Status of Glueballs*, *Prog.Part.Nucl.Phys.* **63** (2009) 74–116, [[arXiv:0812.0600](#)].
  - [5] W. Ochs, *The Status of Glueballs*, *J.Phys.* **G40** (2013) 043001, [[arXiv:1301.5183](#)].
  - [6] J. F. Donoghue, K. Johnson, and B. A. Li, *Low Mass Glueballs in the Meson Spectrum*, *Phys. Lett.* **B99** (1981) 416–420.  
K. Ishikawa, *Is the  $E(1420)$  in  $J/\psi$  Decay a Gluonic Bound State?*, *Phys. Rev. Lett.* **46** (1981) 978.  
M. S. Chanowitz, *Have We Seen Our First Glueball?*, *Phys. Rev. Lett.* **46** (1981) 981.
  - [7] C. Edwards et al., *Identification of a Pseudoscalar State at 1440 MeV in  $J/\psi$  Radiative Decays*, *Phys. Rev. Lett.* **49** (1982) 259. [Erratum: *Phys. Rev. Lett.* 50,219(1983)].
  - [8] C. Patrignani et al., *Review of Particle Physics*, *Chin. Phys.* **C40** (2016) 100001.
  - [9] A. Masoni, C. Cicalo, and G. L. Usai, *The case of the pseudoscalar glueball*, *J. Phys.* **G32** (2006) R293–R335.
  - [10] C. Amsler and F. E. Close, *Is  $f_0(1500)$  a scalar glueball?*, *Phys.Rev.* **D53** (1996) 295–311, [[hep-ph/9507326](#)].  
W.-J. Lee and D. Weingarten, *Scalar quarkonium masses and mixing with the lightest scalar glueball*, *Phys.Rev.* **D61** (1999) 014015, [[hep-lat/9910008](#)].  
F. E. Close and A. Kirk, *Scalar glueball  $q\bar{q}$  mixing above 1 GeV and implications for lattice QCD*, *Eur.Phys.J.* **C21** (2001) 531–543, [[hep-ph/0103173](#)].  
C. Amsler and N. Törnqvist, *Mesons beyond the naive quark model*, *Phys.Rept.* **389** (2004) 61–117.  
F. E. Close and Q. Zhao, *Production of  $f_0(1710)$ ,  $f_0(1500)$ , and  $f_0(1370)$  in  $J/\psi$  hadronic decays*, *Phys.Rev.* **D71** (2005) 094022, [[hep-ph/0504043](#)].  
F. Giacosa, T. Gutsche, V. Lyubovitskij, and A. Faessler, *Scalar nonet quarkonia and the scalar glueball: Mixing and decays in an effective chiral approach*, *Phys.Rev.* **D72** (2005) 094006, [[hep-ph/0509247](#)].  
M. Albaladejo and J. Oller, *Identification of a Scalar Glueball*, *Phys.Rev.Lett.* **101** (2008) 252002,

- [arXiv:0801.4929].  
V. Mathieu, N. Kochelev, and V. Vento, *The Physics of Glueballs*, *Int.J.Mod.Phys.* **E18** (2009) 1–49, [arXiv:0810.4453].  
S. Janowski, D. Parganlija, F. Giacosa, and D. H. Rischke, *The Glueball in a Chiral Linear Sigma Model with Vector Mesons*, *Phys.Rev.* **D84** (2011) 054007, [arXiv:1103.3238].
- [11] S. Janowski, F. Giacosa, and D. H. Rischke, *Is  $f_0(1710)$  a glueball?*, *Phys.Rev.* **D90** (2014) 114005, [arXiv:1408.4921].
- [12] H.-Y. Cheng, C.-K. Chua, and K.-F. Liu, *Revisiting Scalar Glueballs*, *Phys. Rev.* **D92** (2015) 094006, [arXiv:1503.06827].
- [13] F. E. Close and A. Kirk, *Interpretation of scalar and axial mesons in LHCb from a historical perspective*, *Phys. Rev.* **D91** (2015) 114015, [arXiv:1503.06942].
- [14] J.-M. Frère and J. Heeck, *Scalar glueballs: Constraints from the decays into  $\eta$  or  $\eta'$* , *Phys. Rev.* **D92** (2015), no. 11 114035, [arXiv:1506.04766].
- [15] C. J. Morningstar and M. J. Peardon, *The Glueball spectrum from an anisotropic lattice study*, *Phys.Rev.* **D60** (1999) 034509, [hep-lat/9901004].
- [16] Y. Chen, A. Alexandru, S. Dong, T. Draper, I. Horvath, et al., *Glueball spectrum and matrix elements on anisotropic lattices*, *Phys.Rev.* **D73** (2006) 014516, [hep-lat/0510074].
- [17] It has been argued that the pseudoscalar sector may be particularly sensitive to unquenching in Ref. [51], but the estimated effects on the mass were of the order of 15%, whereas almost 50% would be needed to bring the lattice result down to the mass of  $\eta(1405)$ .
- [18] UKQCD Collaboration, C. M. Richards, A. C. Irving, E. B. Gregory, and C. McNeile, *Glueball mass measurements from improved staggered fermion simulations*, *Phys. Rev.* **D82** (2010) 034501, [arXiv:1005.2473].
- [19] E. Gregory, A. Irving, B. Lucini, C. McNeile, A. Rago, et al., *Towards the glueball spectrum from unquenched lattice QCD*, *JHEP* **1210** (2012) 170, [arXiv:1208.1858].
- [20] E.g., the existence of  $\eta(1295)$  is questioned in [3], while Ref. [52] came to the conclusion that there is “no evidence for two separate  $\eta(1405)$  and  $\eta(1475)$  from the present data” and only one  $\eta(1440)$  is actually required. The arguments [9] in favor of two resonances  $\eta(1405)$  and  $\eta(1475)$  instead of one  $\eta(1440)$  and the exclusion of  $\eta(1475)$  as glueball candidate rely also on the fact that the latter was observed in  $\gamma\gamma$  reactions by the L3 experiment [53, 54] (though not by the CLEO experiment [55] despite having a larger data set). Ref. [53] gives an upper limit for the  $\eta\pi\pi$  channel which is about 40% of the signal in the  $K\bar{K}\pi$  channel, thus it may actually be consistent with having a single resonance  $\eta(1440)$  comprising  $\eta(1405)$  and  $\eta(1475)$  which appears in  $\gamma\gamma$  reactions, since in radiative  $J/\psi$  decays  $J/\psi \rightarrow \gamma\eta(1405/1475)$  the  $\eta\pi\pi$  channel is only 16% of the  $K\bar{K}\pi$  channel [8]. (We thank Denis Parganlija for discussions of this point.).
- [21] In Ref. [39] a unique form of the interaction Lagrangian for extended linear sigma models has been posited, where only the coupling strength is left undetermined, but in a subsequent extension [56] more possibilities were introduced.
- [22] A. Rebhan, *The Witten-Sakai-Sugimoto model: A brief review and some recent results*, *EPJ Web Conf.* **95** (2015) 02005, [arXiv:1410.8858].
- [23] F. Brünner, D. Parganlija, and A. Rebhan, *Glueball Decay Rates in the Witten-Sakai-Sugimoto Model*, *Phys. Rev.* **D91** (2015) 106002, [arXiv:1501.07906].
- [24] F. Brünner and A. Rebhan, *Nonchiral enhancement of scalar glueball decay in the Witten-Sakai-Sugimoto model*, *Phys. Rev. Lett.* **115** (2015) 131601, [arXiv:1504.05815].
- [25] F. Brünner and A. Rebhan, *Constraints on the  $\eta\eta'$  decay rate of a scalar glueball from gauge/gravity duality*, *Phys. Rev.* **D92** (2015) 121902, [arXiv:1510.07605].
- [26] E. Witten, *Anti-de Sitter space, thermal phase transition, and confinement in gauge theories*, *Adv.Theor.Math.Phys.* **2** (1998) 505–532, [hep-th/9803131].
- [27] R. C. Brower, S. D. Mathur, and C.-I. Tan, *Glueball spectrum for QCD from AdS supergravity duality*, *Nucl.Phys.* **B587** (2000) 249–276, [hep-th/0003115].
- [28] T. Sakai and S. Sugimoto, *Low energy hadron physics in holographic QCD*, *Prog.Theor.Phys.* **113** (2005) 843–882, [hep-th/0412141].
- [29] T. Sakai and S. Sugimoto, *More on a holographic dual of QCD*, *Prog.Theor.Phys.* **114** (2005) 1083–1118, [hep-th/0507073].
- [30] G. S. Bali, F. Bursa, L. Castagnini, S. Collins, L. Del Debbio, et al., *Mesons in large- $N$  QCD*, *JHEP* **1306** (2013) 071, [arXiv:1304.4437].
- [31] K. Hashimoto, C.-I. Tan, and S. Terashima, *Glueball decay in holographic QCD*, *Phys.Rev.* **D77** (2008) 086001, [arXiv:0709.2208].
- [32] A. Armoni, *Witten-Veneziano from Green-Schwarz*, *JHEP* **0406** (2004) 019, [hep-th/0404248].
- [33] J. L. Barbon, C. Hoyos-Badajoz, D. Mateos, and R. C. Myers, *The Holographic life of the  $\eta'$* , *JHEP* **0410** (2004) 029, [hep-th/0404260].
- [34] N. Anderson, S. K. Domokos, J. A. Harvey, and N. Mann, *Central production of  $\eta$  and  $\eta'$  via double Pomeron exchange in the Sakai-Sugimoto model*, *Phys. Rev.* **D90** (2014) 086010, [arXiv:1406.7010].
- [35] C. Rosenzweig, A. Salomone, and J. Schechter, *A Pseudoscalar Glueball, the Axial Anomaly and the Mixing Problem for Pseudoscalar Mesons*, *Phys. Rev.* **D24** (1981) 2545–2548.
- [36] C. Rosenzweig, A. Salomone, and J. Schechter, *How does a pseudoscalar glueball come unglued?*, *Nucl.Phys.* **B206** (1982) 12.
- [37] In Ref. [35]  $\tilde{G}_1$  is an auxiliary field with wrong-sign mass term that can be replaced by  $\text{Im log det } \Sigma$ , which is essentially  $\eta_0$ , through its algebraic equations of motion.
- [38] C. Rosenzweig, J. Schechter, and C. G. Trahern, *Is the Effective Lagrangian for QCD a Sigma Model?*, *Phys. Rev.* **D21** (1980) 3388.
- [39] W. I. Eshraim, S. Janowski, F. Giacosa, and D. H. Rischke, *Decay of the pseudoscalar glueball into scalar and pseudoscalar mesons*, *Phys. Rev.* **D87** (2013) 054036, [arXiv:1208.6474].
- [40] G. J. Gounaris and H. Neufeld, *Why  $\iota(1460)$  decays mainly into  $K\bar{K}\pi$ ?*, *Phys. Lett.* **B213** (1988) 541. [Erratum: *Phys. Lett.* **B218**, 508(1989)].
- [41] O. Aharony and D. Kutasov, *Holographic Duals of Long*

- Open Strings*, *Phys.Rev.* **D78** (2008) 026005, [[arXiv:0803.3547](#)].
- K. Hashimoto, T. Hirayama, F.-L. Lin, and H.-U. Yee, *Quark Mass Deformation of Holographic Massless QCD*, *JHEP* **0807** (2008) 089, [[arXiv:0803.4192](#)].
- R. McNees, R. C. Myers, and A. Sinha, *On quark masses in holographic QCD*, *JHEP* **0811** (2008) 056, [[arXiv:0807.5127](#)].
- [42] O. Bergman, S. Seki, and J. Sonnenschein, *Quark mass and condensate in HQCD*, *JHEP* **0712** (2007) 037, [[arXiv:0708.2839](#)].
- A. Dhar and P. Nag, *Sakai-Sugimoto model, Tachyon Condensation and Chiral symmetry Breaking*, *JHEP* **0801** (2008) 055, [[arXiv:0708.3233](#)].
- A. Dhar and P. Nag, *Tachyon condensation and quark mass in modified Sakai-Sugimoto model*, *Phys.Rev.* **D78** (2008) 066021, [[arXiv:0804.4807](#)].
- V. Niarchos, *Hairpin-Branes and Tachyon-Paperclips in Holographic Backgrounds*, *Nucl. Phys.* **B841** (2010) 268–302, [[arXiv:1005.1650](#)].
- [43] If we had kept the “exotic” scalar glueball mode  $G_E$  and raised its mass (which is originally only 855 MeV) to the mass of  $f_0(1500)$  or  $f_0(1710)$ , Fig. 1 would look very similar, but the decay width would be about a factor of 10 larger.
- [44] A natural-parity violating coupling of  $\eta_0$  also exists with Reggeons. Fig. 3 gives the parametric order for double Pomeron exchange, which is down by a factor  $1/N_c$  compared to Reggeons, but becomes dominant at sufficiently high energies.
- [45] The production rate of  $\tilde{G}\eta$  has a smaller threshold and thus larger phase space but is reduced by a factor  $(\tan \theta_P)^2 \sim 0.1$ .
- [46] Strictly speaking, the amplitude  $\mathcal{M}(G^* \rightarrow \eta'^2)$  contains contributions proportional to  $\lambda^{-1/2} N_c^{-1} \mathbf{p}_{\eta'}^2$  and  $\lambda^{-1/2} N_c^{-1} m_0^2$ , respectively, with  $m_0^2 \propto \lambda^2 N_f / N_c$ . In the scenario of Ref. [24] (corresponding to that of Ref. [25] with  $x = 1$ ) which we employ here, the decay rate of scalar glueballs in massive pseudoscalar mesons is enhanced by a factor which only depends on the physical masses of the mesons.
- [47] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, *Central exclusive production as a probe of the gluonic component of the  $\eta'$  and  $\eta$  mesons*, *Eur. Phys. J.* **C73** (2013) 2429, [[arXiv:1302.2004](#)].
- [48] F. E. Close and A. Kirk, *A glueball -  $q\bar{q}$  filter in central hadron production*, *Phys. Lett.* **B397** (1997) 333–338, [[hep-ph/9701222](#)].
- [49] A. Kirk, *A review of central production experiments at the CERN Omega spectrometer*, *Int. J. Mod. Phys.* **A29** (2014) 1446001, [[arXiv:1408.1196](#)].
- [50] At larger transverse momentum, the natural-parity violating production of a virtual  $\eta'$  decaying into a scalar and a pseudoscalar glueball also becomes possible, with a cross section involving a factor of  $t_1 t_2 \sin^2 \theta_{pp}$ .
- [51] G. Gabadadze, *Pseudoscalar glueball mass: QCD versus lattice gauge theory prediction*, *Phys. Rev.* **D58** (1998) 055003, [[hep-ph/9711380](#)].
- [52] D. V. Bugg, *Data on  $J/\Psi \rightarrow \gamma(K^\pm K_S^0 \pi^\mp)$  and  $\gamma(\eta \pi^+ \pi^-)$* , [arXiv:0907.3015](#).
- [53] **L3** Collaboration, M. Acciarri et al., *Light resonances in  $K_S^0 K^\pm \pi^\mp$  and  $\eta \pi^+ \pi^-$  final states in  $\gamma\gamma$  collisions at LEP*, *Phys. Lett.* **B501** (2001) 1–11, [[hep-ex/0011035](#)].
- [54] **L3** Collaboration, P. Achard et al., *Study of resonance formation in the mass region 1400 – 1500 MeV through the reaction  $\gamma\gamma \rightarrow K_S^0 K^\pm \pi^\mp$* , *JHEP* **03** (2007) 018.
- [55] **CLEO** Collaboration, R. Ahohe et al., *The Search for  $\eta(1440) \rightarrow K_S^0 K^\pm \pi^\mp$  in two-photon fusion at CLEO*, *Phys. Rev.* **D71** (2005) 072001, [[hep-ex/0501026](#)].
- [56] W. I. Eshraim and S. Schramm, *Decay modes of the excited pseudoscalar glueball*, [arXiv:1606.02207](#).